Review

Insight into pressure-swing distillation from azeotropic phenomenon to dynamic control

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ABSTRACT

Pressure-swing distillation (PSD) is widely used as an efficient method for separating pressure-sensitive azeotropic mixtures in industrial processes. Remarkably, PSD can achieve pure products without introducing a third component compared with extractive distillation and azeotropic distillation. Heat integration into PSD can save energy and reduce operating costs, thus relieving the continuous growth of energy consumption in the distillation industry. This review paper describes the development of this widely used distillation technique, including all of the main aspects related to thermodynamic analysis, Quantitative structure property relationship (QSPR), process design, process intensification, and dynamic control. Based on the foundation of research, further development of PSD is proposed for separating multi-component azeotropic mixtures and exploring the process design and dynamic control from QSPR, aiming at promoting the industrial application of this environmentally friendly and well-known separation technique from multi-scale analysis.

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<table>
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BIP	Binary interaction parameter
DCBR	Double column batch rectifier
DCBS	Double column batch stripper
f_i^{oL}	Liquid fugacity in standard state
HIDiC	Heat integrated distillation column
HP	High pressure
HPC	High pressure column
K_i	Phase equilibrium constant
LP	Low pressure
LPC	Low pressure column
PID	Proportional-integral-derivative
PSD	Pressure-swing distillation
PSBD	Pressure-swing batch distillation
QSAR	Quantitative structure activity relationship
QSPR	Quantitative structure property relationship
Q_R/F	Reboiler heat duty/feed flow rate
RR	Reflux ratio
R/F	Reflux rate/feed flow rate
TAC	Total annual cost
THF	Tetrahydrofuran
VLE	Vapor liquid equilibrium
VRC	Vapor recompression column
α_{ij}	Relative volatility
γ_i^L	Activity coefficient
Φ_i^v	Vapor fugacity coefficient

1. Introduction

Among all of the separation technologies, distillation is currently the most widely used for separating mixtures in industrial process, and distillation consumes approximately 95% of the total energy used in the chemical separation industry (Mahdi et al., 2015). Despite the high energy consumption, distillation is still a preferred process because of its processing advantages and the abundant theoretical and practical knowledge.

Ordinary distillation cannot achieve effective separation when the mixture exhibits the azeotropic phenomenon. If the chemical components are dissimilar and repulsion forces are strong, activity coefficients are greater than unity, thus leading to the formation of minimum boiling azeotropes such as the azeotrope of ethanol/water, tetrahydrofuran (THF)/water, acetone/methanol. If the chemical components attract each other, activity coefficients are less than unity, and maximum boiling azeotropes, such as water/ethylenediamine, methanol/trimethoxysilane can form (Luyben, 2012, 2013a). Azeotropes are also classified in terms of the number of phases (homogeneous and heterogeneous azeotropes) and in terms of the number of components (binary and multi-component azeotrope). Special distillation methods, including azeotropic distillation (Honghai et al., 2015; Li et al., 2015b; Yu et al., 2015), extractive distillation (An et al., 2015; Luyben, 2015; You et al., 2015), and pressure swing distillation (PSD) (Luyben, 2013a; Muñoz et al., 2006; Mulia-Soto and Flores-Tlacuahuac, 2011; Qasim et al., 2015), are common ways for separating azeotropes. PSD has been widely studied and applied in the industry for its superiority qualities of introducing no entrainer, protecting the environment, and saving energy by heat integration.

The PSD separation is based on the fact that a mixture of components displays sensitivity to pressure, which means that a simple change in pressure can alter the relative volatilities of the components of the mixture with close boiling points or form an azeotrope. The pressure-sensitivity of azeotropes has been known since the 1860s (Roscoe, 1860, 1862; Roscoe and Dittmar, 1860). Since then, the effect of pressure on the azeotropic mixtures has been explored in many papers from theoretical and experimental studies (Abildskov and O'Connell,

2015; Horsley, 1947; Knapp, 1991; Wasylkiewicz et al., 2003). Lewis (1928), to our knowledge, is the first to apply this property to distillation of azeotropes.

PSD can be divided into three types according to the operating mode: continuous PSD, pressure swing batch distillation (PSBD), and semi-continuous PSD. Many scholars and researchers have focused on the azeotrope separation with PSD in these three operating modes. Table 1 lists the information on PSD separation of azeotropes in published articles. Continuous PSD is widely used to separate binary azeotropes, and the flowsheet includes two columns operating at different pressures or a single shell column that is divided into two sections, the high pressure (HP) section and the low pressure (LP) section (Mulia-Soto and Flores-Tlacuahuac, 2011). High purity products can be obtained at the bottom of distillation columns (minimum boiling azeotropes) or the top of distillation columns (maximum boiling azeotropes). Repke et al. (2007) explored the application of PSD for separating a binary azeotrope experimentally for the first time in a batch rectifier and in a stripper. In PSBD with one column (Klein and Repke, 2009; Repke et al., 2007), the feed is charged into a bottom tank (regular batch) or into a top tank (inverted batch), and the initial feed composition determines whether the first step is LP or HP. High purity products are obtained at the bottom of the PSBD column. The other PSBD mode is the double-column system (Modla, 2010; Modla and Lang, 2008a, 2010; Modla et al., 2010), which is the combination of two rectifying sections or two stripping sections. The double-column system contains a double column batch rectifier (DCBR), which is more suitable for maximum boiling azeotropes from the standpoint of energy consumption with same product quality, and the double column batch stripper (DCBS), which is more economic for minimum boiling azeotropes (Modla and Lang, 2008a). Phimister and Seider (2000) investigated the separation of a minimum boiling azeotrope by semi-continuous PSD. The semi-continuous PSD includes one column, and the distillation column is adjusted from LP to HP in a cyclic campaign.

Another classification method for PSD depends on the number of components in the mixture to be separated. Following this criterion, PSD can be divided into two types, binary mixture PSD (Fulgueras et al., 2016, 2015; Luo et al., 2014) and multi-component PSD (Modla and Lang, 2008b; Modla et al., 2010; Zhu et al., 2016). Some binary close-boiling hydrocarbon mixtures can also be separated by continuous PSD to save energy (Zhang et al., 2014). Many scholars investigated the separation of binary azeotropes with PSD, but the separation of multi-component mixtures (at least one binary azeotrope exists) with PSD is insufficiently studied, especially regarding the continuous PSD. Knapp and Doherty (1992) noted that the continuous PSD will be unlikely to be advantageous compared with extractive distillation for more columns and higher recycle ratios may be needed when more than one distillation boundary is present. Modla (2011b) studied the feasibility and simulation of PSBD separation of ternary homoazeotropic mixtures with different column configurations in published studies.

Despite the above-mentioned advantages to the process, some limitations and challenges remain for PSD. The limitations of PSD are considered mainly from three aspects. First, PSD is focused mainly on pressure-sensitive azeotropes, and it is impossible or energy intensive to separate azeotropes with low sensitivity by the change of pressure (Luyben, 2012). Second, some heat-sensitive azeotropic components may decompose with the increasing pressure, and this heat sensitivity prevents the application of PSD. Third, if a vacuum pressure is used in PSD, some cooling media that are much more expensive than cooling water may be needed, thus causing more operating costs for PSD. In our opinion, the quantitative structure-property relationship (QSPR) resolves the characterization of azeotropic characteristics by using molecular descriptors of azeotropic components well (Katritzky et al., 2011; Solov'ev et al., 2011). However, no papers have focused on the characterization of the vapor liquid equilibrium (VLE), steady state design, and dynamic control of PSD with QSPR. The challenges of PSD are quantitative analysis of the VLE, steady state design, and dynamic control by using QSPR, and these challenges will be described in the following content.

Due to the wide use of PSD, there have been several review papers in some journals and chapters in books dealing with the separation